TNO Physics and Electronics Laboratory

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TD 93-2783

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TNO-report

FEL-93-B160

copy no.

title

High Performance Computing for Medical Image Interpretation

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TNO-report
FEL-93-B160

copy no.

title

High Performance Computing for Medical Image Interpretation

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date:

October 1993

classification

classified by	: P.L.J. van Lieshout
classification date	: October 1, 1993
title	: Ongerubriceerd
managementuittreksel	: Ongerubriceerd
abstract	: Ongerubriceerd
report text	: Ongerubriceerd
no. of copies	: 50
no. of pages	: 72 (excluding RDP and distribution list)
no. of appendices	: -

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Netherlands organization for applied scientific research

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MANAGEMENTUITTREKSEL

Titel : High Performance Computing for Medical Image Interpretation

Auteur(s) : Dr.ir. A.C.M. Dumay

Datum : Oktober 1993

Rapport no. : FEL-93-B160

High Performance Computing (HPC) technologie omvat het op schaalbare wijze aanwenden van methoden voor parallel en gedistribueerd rekenen. Deze technologie is sterk in opkomst vanwege de vele applicaties die nu realiseerbaar worden. FEL-TNO heeft in de afgelopen jaren haar expertise op het gebied van de HPC hard- en software-ontwikkeling dan ook aanzienlijk uitgebreid ten behoeve van zowel Defensie als de civiele markt. De geneeskunde/ gezondheidszorg is één van de gebieden waarin Defensie en de civiele markt elkaar deels overlappen. Om de herbruikbaarheid van onderzoeksresultaten na te streven, ligt het voor de hand om eerst de geneeskunde/gezondheidszorg "in kaart te brengen" gezien vanuit Defensie en de civiele markt.

Het doel van het onderzoek is dan ook het geven van een overzicht van mogelijke gebieden in de geneeskunde/gezondheidszorg waar High Performance Computing nodig wordt geacht vanuit de visie van de eindgebruiker. Daarnaast wordt een mogelijke wijze voorgesteld om de markt voor deze gebieden te benaderen.

Deze medische gebieden worden met zekere details omschreven, teneinde een begrip voor de toepassingsgebieden na te streven. In alle onderzochte toepassingesgebieden staat beeldinterpretatie centraal. Medische beeldinterpretatie door beeldverwerking behelst het verbeteren van de kwaliteit van beelden teneinde medische diagnostiek, therapie en chirurgie te ondersteunen. Globaal zijn er vier onderdelen in het beeldverwerkingsproces, te weten: i) datafusie; ii) object/kenmerk-extractie; iii) analyse en iv) visualisatie. Met de introduktie van de Computer Tomografie (CT) en beeldvorming op basis van Magnetische Resonantie (MRI) kunnen driedimensionale (3D) beelden worden gemaakt van het inwendige van de mens. Het bewerken van 3D beelden op zodanige wijze dat de tijd die daarvoor nodig is binnen aanvaardbare grenzen blijft, maakt het gebruik van High Performance Computing technieken wenselijk. Huidige (commerciële) implementaties behalen niet de performance die vereist is in de medische kliniek, waardoor routinematig gebruik veelal tegen hoge personeelskosten wordt

uitgevoerd. Modules voor 3D datafusie, 3D object/kenmerk-extractie, analyse en 3D visualisatie zouden in bestaande en nog te ontwikkelen medische systemen kunnen worden gepast voor interactieve visualisatie, quantitatieve analyse, (inverse) radiotherapieplanning, neurochirurgie-planning en ondersteuning tijdens het uitvoeren van operaties. Geïntegreerd in een High Performance Computing Medical Image Interpretation System (HIPMI^{2}S) kunnen deze modulen aangewend worden voor de ontwikkeling van anatomische modellen (databases) voor simulatoren en trainingsystemen in Virtual Environments voor b.v. de evaluatie van protocollen voor de behandeling van patiënten onder trauma-omstandigheden (triage), chirurgie, rehabilitatie en telemedicine. Met name triagetraining in Virtual Environments zou voor Defensie van nut kunnen zijn gelet op de toenemende behoefte aan kwalitatief hoogwaardige opleidingsfaciliteiten. Toepassingen van telemedicine zijn voor Defensie van belang daar waar er sprake is van toenemende mobiliteit van eenheden en inzetbaarheid in landen met onvoldoende geneeskundige infrastructuur.

In de literatuur zijn een groot aantal methoden beschreven voor de realisatie van bovengenoemde toepassingen. Daarin wordt (nog) zeer weinig gebruik gemaakt van HPC-technologie. De realisatie van een modulair opgebouwd "High Performance Computing Medical Image Interpretation System" (HIPMI^{2}S) geeft FEL-TNO de mogelijkheid om haar expertise aan te bieden aan de Nederlandse en Europese civiele medische industrie voor beeldverwerking en training, en de mogelijkheid om anatomische modellen te realiseren en te visualiseren als essentieel onderdeel van training- en simulatiesystemen in Virtual Environments voor de militaire geneeskunde.

ABSTRACT

The objective of this report is describing a brief inventory of potential areas in medicine where High Performance Computing (parallel and distributed computing) technology is needed from an end-user's point of view. The potential areas are described in detail to give an understanding of what it is all about.

The commonality in all these areas is image interpretation. Medical image interpretation by processing aims at improving image quality and helping image analysis in order to support medical diagnosis, therapy and surgery. Globally, four subjects can be distinguished, including: i) data fusion; ii) object/feature extraction; iii) analysis and iv) visualisation.

With the introduction of Computer Tomography (CT) and Magnetic Resonance Imaging (MRI) three-dimensional (3D) images can be acguired from patients. The processing of 3D images such that the time required for that purpose is within acceptable limits makes the use of High Performance Computing (HPC) techniques desirable. Currently (commercially) available implementations do not satisfy the performance requirements for routine use in a clinical setting, as a result of wich such systems will be used at high costs of personnel.

High Performance Computing Medical Image Interpretation include data fusion, object/feature extraction, analysis and visualisation of 3D medical images. Modules for these purposes may be intregrated in existing medical systems to support interactive visualisation, quantitative analysis, (inverse) radiotherapy planning, neurosurgery planning and intraoperative assistance. Intregrated into a High Performance Computing Medical Image Interpretation System (HIPMI^{2}S) one has the tools for developing anatomical models (databases) for simulation and training in Virtual Environments for, e.g. protocol evaluation under trauma conditions (triage), surgery, rehabilitation and telemedicine.

SAMENVATTING

Het doel van het voorliggende rapport is het geven van een overzicht van mogelijke gebieden in de geneeskunde waar *High Performance Computing* (parallel en gedistribueerd rekenen) nodig wordt geacht vanuit de visie van de eindgebruiker. Deze medische gebieden worden met zekere details omschreven, teneinde een begrip voor de toepassingsgebieden na te streven.

In alle toepassingsgebieden staat beeldinterpretatie centraal. Medische beeldinterpretatie door beeldverwerking behelst het verbeteren van de kwaliteit van beelden teneinde medische diagnostiek, therapie en chirurgie te ondersteunen. Globaal zijn er vier onderdelen in het

beeldverwerkingsproces, te weten: i) datafusie; ii) object/kenmerk-extractie; iii) analyse en iv) visualistatie.

Met de introduktie van de Computer Tomografie (CT) en beeldvorming op basis van Magnetische Resonantie (MRI) kunnen drie-dimensionale (3D) beelden worden gemaakt van het inwendige van de mens. Het bewerken van 3D beelden op zodanige wijze dat de tijd die daarvoor nodig is binnen aanvaardbare grenzen blijft, maakt het gebruik van High Performance Computing (HPC) technieken wenselijk. Huidige (commerciële) implementaties behalen niet de performance die verreist is in de medische kliniek, waardoor routinematig gebruik veelal tegen hoge personeelskosten wordt uitgevoerd.

High Performance Computing voor medische Beeldinterpretatie omvat datafusie, object/kenmerk-extractie, analyse en visualisatie voor 3D medische beelden. Modules voor deze doeleinden zouden in bestaande en nog te ontwikkelen medische sytemen kunnen worden gepast voor interactieve visualisatie, quantitatieve analyse, (inverse) radiotherapieplanning, neurochirurgieplanning en ondersteuning tijdens het uitvoeren van operaties. Geïntregeerd in een High Performance Computing Medical Image Interpretation System (HIPMI^{2}S) kunnen anatomische modellen (databases) worden ontwikkeld voor simulatoren en trainingsystemen in *Virtual Environments* voor b.v. de evaluatie van protocollen voor de behandeling van patiënten onder trauma-omstandigheden (triage), chirurgie, rehabilitie en telemedicine.

CONTENTS

PREFACE

This document contains an introductory overview (Chapter 1) to the field of medical imaging, in which the various imaging modalities are characterised. So far, the consulting physician comes to a diagnosis of possible diseases on the basis of the evaluation of the results of all outcomes of the imaging modalities, eventually assisted by computer systems. There is no single computer system known that integrates the potentials of the individual imaging modalities into a consistent diagnosis. This is mainly attributed to the huge computational task to be performed in order to process, analyse, interpret and combine all data. With the recent development of High Performance Computing (HPC) techniques this task may be handled.

HIPMI^{2}S (Chapter 2) is a High Performance Medical Image Interpretation System that will make use of the latest technology in the field of high performance computing (HPC) to perform the task of integrating multi-modality data. The outcome of HIPMI^{2}S can be used for scientific visualisation purposes (diagnostics), robot control in (neuro-)surgery, neurosurgery planning, radiotherapy planning and the construction of Virtual Reality-based training systems. Therefore, advanced algorithms for 3-D image interpretation have to be adapted towards the latest achievements in the field of HPC (Chapter 3). The organisation of the computer system (Chapter 4) and software system (Chapter 5) are suggested while image formats are listed (Chapter 6). To have easy access to all data at all levels at all times an advanced database management system (Chapter 7) is proposed. Readily available image processing techniques (Chapter 8) and pattern recognition techniques (Chapter 9) are collected and elaborated upon (Chapter 10). The evaluation of techniques and a demonstration system can be found in Chapter 11. Chapter 12 highlights the many facets of the management of computing and information. The legal aspects of computing, including patents, are considered in Chapter 12 as well. A possible market approach is described in Chapter 13.

1 INTRODUCTION TO MEDICAL IMAGING

1.1 Imaging systems in medicine

Imaging systems are applied in roughly three areas[1] of the field of medicine:

i) diagnosis;
ii) therapy;
iii) surgery.

These areas have a certain amount of overlap and applications can be found for both experimental and clinical medicine. The largest area of these three is diagnosis, including:

i) radiology;
ii) nuclear medicine.

In radiology, the following imaging modalities can be found:

i) Conventional X-ray imaging (2-D X-ray imaging);
ii) Computer Tomography (CT) (3-D X-ray imaging);
iii) Magnetic Resonance (MR) imaging (3-D nuclear magnetic resonance imaging);
iv) Magnetic Resonance Angiography (MRA) (3-D nuclear magnetic resonance imaging of (coronary) arterial systems);
v) Angiography (2-D X-ray imaging of arterial systems);
vi) Digital Subtraction Angiography (DSA) (2-D background-subtracted X-ray imaging of arterial systems);
vii) Arteriography (2-D X-ray imaging of coronary arterial systems);
iix) Dual Energy Imaging (2-D subtracted dual energy X-ray imaging).

Conventional X-ray imaging is carried out with a single X-ray source-image intensifier system. The X-rays are emitted by the source, attenuated by body organs and fall upon the input screen of the detector system, which is part of the image intensifier. The various organs can be characterised by their linear attenuation coefficient. This gives rise to shadow patterns from which the diagnoses can be made. A general problem arising from this modality is the detection of small

1 From the physics point of view one can distinguish three types of data: transmission, emission and reflection data.

details especially if their density is quite similar to that of the surrounding area. Current research aims at developing detector systems with high image contrast (Amplified Multiple Beam Ecquilaisation in Radiology, AMBER), image contrast enhancement techniques (Delfino (1987), Andress and Wilson (1991), Kheilaf et al. (1991)) and filmless systems (e.g., Shaber et al. (1989)). The images are usually stored on cinefilm and, recently, also in digital format (digital radiography) (Snoeren (1991)). Conventional X-ray imaging is applied in, e.g., chest radiography and orthodontics (Scott and Symons (1982)).

Computer Tomography (CT) applies to all techniques by which transaxial slices of an object are reconstructed from X-ray transmission projection data. Radon (1917) laid the mathematical basis of many reconstruction algorithms. He described the projection by transmission of an object, the Radon transform, and the reconstruction of the object from the projection data, the inverse Radon transform. The first practical implementations of the inverse Radon transform in the field of medicine were described by Cormack and Hounsfield, who shared a Nobel prize (1972) for this breakthrough in medicine. Their results (e.g., Cormack (1963, 1964) and Hounsfield (1973)) initiated an avalanche of publications on implementations of the inverse Radon transform. The implementations varied in the handling of the projection geometry, the interpolation techniques involved, the filtering/windowing functions and constraints imposed by the number of projections (Herman (1980), Kak and Slaney (1987), Natterer (1986)). From the diagnostic point of view, these algorithms show a large variety in performance (Vannier et al. (1989)).

The reconstruction of organs in motion, like the beating heart, from X-ray projection data requires complex scanning devices for ultra fast data acquisition and reconstruction. At present, two such systems are known: the commercially available Imatron C100 (Boyd and Lipton (1983)) and the experimental Dynamic Spatial Reconstructor (DSR) (Ritman, Robb and Harris (1985)). Research in the field of quantitative CT is directed towards, among others, flow velocity (Song and Leahy (1991)) while High Performance Computing (HPC) techniques have only recently been introduced into CT (Cheng et al. (1990)).

Magnetic Resonance Imaging (MRI) is a diagnostic technique to measure and display cross sections of human organs. Therefore, the Fourier coefficients of the proton spin density of tissue are acquired and reconstructed. The Fourier coefficients are acquired with the aid of magnetic fields by which the spins of hydrogen atoms in the human body are forced to emit radiation with a characteristic frequency at each point. There are 4 types of magnetic fields involved (Hinshaw

and Lent (1983)):

i) a strong homogeneous field to allign the spins in the z-direction; the z-direction is the equilibrium direction of the spins;
ii) a radio frequency pulse (rf-pulse), i.e., a rotation electromagnetic field in the xy-plane, which is applied for a very short time to force the spins out of equilibrium;
iii) the z-component of the gradient vector, by which a cross section is selected;
iv) the magnetic gradient field, which forces protons at a selected position to resonate with a unique frequency.

The magnetisation, which is the spin density at a selected position and time, follows the so-called Bloch equation. In this equation arise two relaxation parameters, T1 and T2, that represent the effect of the relaxation process of the spins.

T1 is the longitudinal or spin-lattice relaxation time which governs the evolution of the spin density in the z-direction towards its equilibrium value. T2 is the transverse or spin-spin relaxation time which governs the evolution of the magnitude of the transverse spin density towards its equilibrium value zero. In general, T1 is much larger than T2. The receiver coil of the MR-acquisition system measures the magnetisation before it has returned to equilibrium and an output signal is generated The signals collected in a single plane are reconstructed into a cross sectional image, while a set of such cross sections define a reconstructed volume (Morris (1986)).

Magnetic Resonance Angiography (MRA) is the visualisation of vessels (both arterial and venous structures) with MRI. Dispite the limited spatial resolution of MRI, the potential of visualising vessels by magnetic resonance imaging techniques has been demonstrated (Laub and Bachus (1987)). Research into this field is still at hand, especially aiming at flow velocity analysis (Izen and Haacke (1990)) and tagging techniques (Prince and Veigh (1992)), and techniques to reduce the data acquisition time (Zwaan (1991)). Clinical research aims at developing and applying intravascular contrast dyes, like Gadolineum DTPA. Although MRA is still in an experimental phase, it has some potential advantages, particularly with respect to coronary and cerebrovascular imaging. Firstly, blood vessels can be visualised without the injection of contrast dye. Secondly, MRA produces direct 3-D images which can be viewed from any position. Thirdly, it permits the visualisation of vascular morphology and pathology, simultaneously with myocardial or cerebral tissue discrimination. This latter feature is particularly appealing for stereotactic planning using one single procedure, since it makes the complex matching of different imaging modalities (DSA,

CT, MR) obsolete.

Angiography makes the visualisation of vessel possible. Arterial vessels carry blood from the heart to the muscles and body organs while veins carry the blood to the heart. Imaging of vessels by X-ray techniques has become indispensable to present day medical practice. To visualise blood vessels, a contrast dye is injected through a catheter positioned at the orifice of the arterial system of interest or in the venous system when veins are being examined. A sequence of images shows the dilution of the dye with blood and the progression of this mixture. The sequence can be acquired at a speed of 25 images per second, which is a European standard, or 30 images per second, which is an American standard. Several sequences are usually acquired from different angiographic views. Complex protocols (e.g., Dumay (1992)) are carried out in procedures, generally called catheteri-sation. The projected sizes of vessel segments provide information about the location and severity of possibly existing stenoses. The introduction of Quantitative (Coronary) Angiography (QCA) techniques (e.g., Reiber and Serruys (1991)) has made it possible to obtain parameters which are objective and reproducible from a morphology point of view and functionality point of view (Kirkeeide (1991)).

Digital Subtraction Angiography (DSA) visualises the progression of the (coronary) blood circulation by digital enhancement in two ways. First, by mask-mode subtraction through serially subtracting the selected image before contrast medium injection from subsequent images at the same phase of the pulsatile blood flow (heart cycle). ECG[2]-gated images are acquired to eliminate artefacts resulting from cardiac motion. Second, by gated-interval-time-differencing where each image is subtracted from the corresponding image in the next heart beat. In the latter case the resultant images visualise only new appearance of contrast medium rather than their instantaneous content. DSA is used in patients which cannot be exposed to the radiation dosage that is used in conventional angiography and in the investigation of time-related phenomena (Verhoeven (1985)).

Arteriography is basically the same as angiography though the techniques are applied to the coronary arteries that supply blood to the heart muscle (myocardium). Research in this field aims primarily at developing techniques for 3-D reconstruction from a very limited number of projections (Dumay (1992)) and (intracoronary) echocardiography (Rijsterborgh (1990)). Clinical

2 Electro cardiogram.

research aims at developing and improving intervention techniques like Percutaneous Transluminal Coronary Angioplasty (PTCA) (Serruys et al. (1991)) and stenting (Strauss (1991)).

Dual Energy Imaging is very similar to DSA, however, the mask-images are not selected under pre-contrast dye injection conditions, but with a different voltage and current of the X-ray tube. This results in X-radiation with different energy levels. The subtraction of the acquired sets of images show the body parts of interest with better image contrast than when the subtraction is omitted.

In Nuclear Medicine, two imaging modalities can be found:

i) Single Photon Emission Computer Tomography (SPECT) (3-D gamma imaging);
ii) Positron Emission Tomography (PET) (3-D positron imaging).

Single Photon Emission Computer Tomography (SPECT) provides techniques to reconstruct the gamma-radiation distribution over an object in 3-D from emission projection data. The images are usually reconstructed using Filtered Backprojection (FB) techniques with filter specifications (King (1983), Hentea and Hawman (1987)) adapted to the sensor system (Modulation Transfer Function, MTF) and object characteristics (Prati (1987)). Research towards statistically-based reconstruction techniques in this field is in full swing (Ollinger (1990), Liow and Strother (1991)).

With SPECT the metabolism of a radiolabelled carrier with tissue can be visualised. The total amount of uptake of a nuclear tracer depends on the blood supply to the tissue cells and the blood (or oxygen O2) demand (L'Abbate (1991), van der Wall et al. (1991)). Automated techniques for analysis purposes are more or less accepted in clinical practice (Nuyts (1991)).

Positron Emission Tomography (PET) has become a powerful tool to measure regional, in vivo distributions of various compounds. Quantitative, functional data are generated, which provide insights into the pharmacological and physiological behaviour of tissue. PET tracers presently in use enable the study of blood flow, metabolism and receptor bindings in humans. With the continuing developments in high resolution PET detectors the possibilities exist, in the first place in experimental animals, to measure full, regional tissue time course of the tracer in individual animals. The benefits of following the arterial time course using noninvasive sampling are apparent in terms of time saved in catheterization and patient discomfort.

One of the main problems which has to be addressed in the design of positron tomographs is the optimization of the spatial resolution while still maintaining detection efficiency: reducing the input crystal size in 2-D arrays in order to achieve higher resolution results in lower light collection efficiency and energy resolution (Rajeswaran et al. (1992)). High performance computing techniques have already been applied in PET imaging (Wilkinson et al. (1989), Barresi et al. (1990)).

Ultrasound Techniques are non-invasive and can be applied under bedside conditions. Quantitative ultrasound has become an important diagnostic tool in clinical decision making, especially in cardiology. The measurement of specific parameters of organ function by cross-sectional echography and by Doppler echography help to differentiate between normal and abnormal function and to assess the severity of the disease. At present, the reproducibility and calibration of echo(cardio)graphic images is limited (Bohs and Trahey (1991), Ten Cate et al. (1991)), which makes quantification of ultrasound images a tedious task (Rijsterborgh (1991)). Transoesaphageal echo transducers provide unrestricted access to ultrasonic sectional images of the heart, but is limited by varying transducer positions and thus produce different imaging planes. Technological developments aim at 3-D acquisition of images of the beating heart (Wollschlager et al. (1989)) which are applied during cardiac surgery to monitoring the conditions of the heart.

Images produced by these imaging modalities are used for visual interpretation and computer-assisted analysis (van der Wall (1992), Marcus et al. (1991)).

In therapy, the forementioned imaging modalities are used to evaluate intervention techniques (e.g., Serruys et al. (1991)) and radiotherapy planning.

In surgery, the forementioned X-ray imaging modalities are used for planning (especially for neuro-surgical planning and stereotactic surgery).

Radiotherapy requires careful planning in order to deliver a sufficient level of radiation to the target tissue while minimising the dose to surrounding (healthy) tissues. Today, there exist many elaborate computer programs, which allow the computation of mor eor less complex treatment plans, but the step to dynamic therapy methods has not yet been taken due to the increase of the computation time. Consequently, the methods involved are not applicable in daily routine, since

conventional computer equipment cannot meet the constraints of interactive computer simulation.

Inverse Radiotherapy Planning (IRP) and Conformal Radiotherapy Planning (SRP) (Webb 1989, 1991a, 1991b, 1992) involve the computation of the position and energy level of the radiation source, given the position and size of the body organ to be treated and satisfying the constraint to minimally damage other body parts.

Stereotactical (neuro-) surgery requires the assessment of the target volume and position as prerequisites for successful treatment planning of brain tumours (Nuyts (1991)). During the operation an electrode is directed into the target area. At that region, nerve fibers should be distroyed for therapy by electrothermo-coagulation. Unfortunately, the target area, at which the nerve fibres should be coagulated, cannot directly be obtained from neuro-anatomical structures displayed by X-ray (including CT-scans) or MRI. Therefore, the area of interest is explored conventionally by electrophysiological stimulations, done by an electric stimulator when the electrode had reached that region. According to sensory or motoric reactions of the patient after such stimulations the region at which coagulations should be carried out most often can be localised by that method. Research in this field aims at referring stimulation and coagulation sites to anatomical structures (Nuyts (1991)).

1.2 2-D image interpretation

Planar (2-D) images are acquired with the use of X-ray techniques and ultrasound techniques. The interpretation of these images requires:
i) object extraction (segmentation);
ii) object feature extraction (analysis);
iii) feature interpretation (classification).

To achieve these goals, a great number of techniques are available from literature. These techniques perform with more or less success under laboratory conditions and some of them have found their way to the clinics. Especially techiques operating on 3D images lack the performance required for routine use. To extract objects from images general purpose and dedicated filtering, and knowledge-based techniques are available. Analysing an object requires domain-knowledge which makes generalisation difficult. To classify an object, the domain of pattern recognition can be exploited.

1.3 3-D image interpretation

All that applies to 2-D image interpretation applies to 3-D image interpretation as well. However, to gain the full potential from the additional dimensionality multi-resolution techniques should be applied to extract objects from the data.

1.4 Advanced medical imaging applications

Advanced medical imaging applications can be found in:

i) computer-assisted stereotactic neurosurgery;
ii) (reconstructive) surgery simulation;
iii) computer integrated manufacturing (CIM) of reconstructed bone structures;
iv) radiation-therapy planning;
v) anatomical encyclopaedia.

Computer-assisted stereotactic neurosurgery is defined as the flexible, on-line, intelligent and integrated use of all available radiological, patient-specific data as well as anatomical, generic models extracted from stereotactic atlases. Images are acquired using a patient-fixed stereotactic frame with accessory locating devices for CT, MRI and DSA. A first step is the localisation of the landmarks in all images. Up to now the positions of these landmarks are manually defined. The landmarks enable the transformation of all image data to the stereotactic frame coordinates. Lesions are (usually manually) outlined in CT and MR images. Finally, all data are made available for stereotactic planning and confirmation of electrode positioning. With interactive simulation the electrode trajectory can be visualised and a full-safe trajectory can be chosen, avoiding cerebral vessels and vulnerable anatomical regions. Image data can be reorganised in slices perpendicular to the surgical probe, offering additional orientation and confirmation clues to the surgeon (Vandermeulen (1991)). An overview of currently available stereotactic frames can be found in Kelly (1991). During the operation an electrode is directed to a target area. At that region, nerve fibers should be distroyed for therapy by electrothermo-coagulation. Unfortunately, the target area, at which the nerve fibres should be coagulated, cannot directly be obtained from neuro-anatomical structures displayed by X-ray (including CT-scans) or MRI. Therefore, the area of interest is explored conventionally by electrophysiological stimulations, done by an electric stimulator when the electrode had reached that region. According to sensory or motoric reactions of the patient after such stimulations the region at which coagulations should be carried out most often can be localised by that method. Research in this field aims at referring stimulation and

coagulation sites to anatomical structures.

Reconstructive surgery simulation allows the visualisation of the results of reconstructive surgery on the basis of analysed CT or MR images. Prototype systems can be found in the area of craniofacial surgery (McEwan (1989)).

Minimal Access Surgery (MAS) or Minimally Invasive Surgery (MIS) is a rather new technique emerging from the field of laparoscopy. Following MAS protocols, instruments for surgery and miniscule light sources are inserted into the human body through natural openings or small holes cut for that purpose. With minimal damage to the outside of the patient, surgery procedures can be carried out. Training of these procedures, however, requires postmortem animal and human bodies, and living volunteers. Training of these procedures in a Virtual Environment would makes these prerequisites immaterial.

However, at present there is little known about mathematical models of deformable soft bodies and, consequently, research in this field is required.

Computer integrated manufacturing of reconstructed bone structures has been demonstrated by, e.g., Schitz et al. (1989), who made use of processed CT images, manually adapted geometric models and numerically-controlled manufacturing equipment.

Radiation-therapy planning can be carried out with similar techniques as used in computer-assisted stereotactic neurosurgery. These techniques must be extended with dose calculation, especially with methods for Iverse Radiotherapy Planning (IRP) and Conformal Radiotherapy Planning (CRP) (Webb 1989, 1991a, 1991b, 1992). For radiotherapy planning, the target area is to be exposed to radiation such that surrounding tissue is minimally exposed. The radiation dose to be calculated depends on the nature of the pathology, the tissue in which it manifests, the structures to be irradiated and the location of the target area.

Anatomical encyclopaedia are useful for educational and diagnostic purposes. An important task of the pathologist is the classification and grading of tissue abnormalities by visual examination of histologic and cytological slides in the context of the clinical history of the patient. The interpretation of the images by the pathologist may involve consultation of textbooks and colleagues for reference. A pathology diagnosis covers a range of tissue abnormalities. Due to

differences in education and experience, experts do not always use the same criteria for defining such a range and they may also differ in their interpretation of findings. As a result, experts may disagree about the diagnosis of a case. Techniques, some of them involving computer applications, have been developed to enhance consistency in pathology diagnosis. With respect to their goals, van Ginneken (1989) divides these techniques into two main categories:

i) increasing objectivity in the acquisition and interpretation of diagnostic data;
ii) promoting the accessibility and utilisation of reference knowledge for classification and grading.

The first category includes morphometry, image processing and statistical pattern recognition, whereas the second category encompasses the computerisation of patient archives, the storage of pictures on optical discs and decision support systems. Though these techniques and computer applications perform their specific tasks adequately, they share one or more of the following limitations (van Ginneken (1989)):

i) limited applicability and scope;
ii) too much emphasis on decision support based on findings solely;
iii) poor facilities for knowledge acquisition.

Atlases of the human anatomy are readily available. Visualisation of the anatomy in a virtual environment has not been demonstrated yet, though pioneering work towards that purpose is under way (Satava (1993), Dumay and Jense (1993), Dumay (1993)).

2 HIPMI²S

2.1 Introduction

A High Performance Medical Image Interpretation System (HIPMI²S) is constructed from hard- and software modules for :

i) fusing 3-D medical images from multiple modalities;
ii) extracting objects from 3-D data;
iii) delineating object features;
iv) interpreting the object features by model-based techniques;
v) interactive visualisation.

This chapter is dedicated towards specifying explicitly the purpose of HIPMI²S and summing up the system and functional requirements.

2.2 Purpose of the system

HIPMI²S imports (series of) volume data from multiple medical imaging modalities like Computer Tomography (CT) scanners, Magnetic Resonance (MR) scanners, Single Photon Computer Tomography (SPECT) scanners and Positron Emission Tomography (PET) scanners. With HPC implementations one may acquire state-of-the-art building blocks for data fusion, object/feature extraction, analysis and visualisation. With these building blocks a treatment planning system for a wide range of applications in computer-assisted surgery and radiotherapy planning systems can be compiled. These systems should have a performance and reliability that suits clinical requirements. On the other hand, the modules should be flexible enough to adapting to future developments in both hard- and software technology. With the modules of HIPMI²S, anatomical models of (parts of) the human body can be extracted and stored into databases embedded in Virtual Reality systems for training and simulation.

HIPMI²S processes the individual volume data-sets by:

i) object segmentation;
ii) object feature extraction;
iii) model-based object interpretation;
iv) object analysis,

and applies data fusion (c.f., e.g., McShan and Fraass (1987), Hawkes et al. (1992) and van den Elsen et al. (1993) and van den Elsen (1993)) at appropriate levels of the data processing.
HIPMI^{2}S responds with:

i) data fusion of selected 3-D images;
ii) highly reliable and reproducible object shape and position representations;
iii) accurate and reproducible descriptions of selected object features;
iv) high performance (interactive) visualisation.

The concept of HIPMI^{2}S is certainly not unique. Both the idea to apply it to radiotherapy (Wernet et al. (1987)) and stereotactic (neuro-) surgery (Doll et al. (1987), Kwoh et al. (1987), Lipinski et al. (1987), Vandermeulen (1991)) are borrowed from the literature. A tutorial on presentation techniques in medical visualisation techniques can be found in, e.g., Pizer and Fuchs (1987). In the field of stereotactic surgery THE VIEWING WAND[3] is commercially available, while for treatment planning the SLP 3-D Treatment PLanning[4] system is available. There are no commercially available training and simulation systems known. What is new to this concept is the fact that High Performance Computing techniques are introduced to achieve a high level of user-friendliness which most (if not all) interactive systems lack in handling 3-D images.

2.3 System requirements

The following constraining requirements must be satisfied by the system configuration:

i) memory capacity to handle data-sets up to 512x512x512 voxels with 12 bits voxel data;
ii) 19" flicker-free RGB video display monitor (1280x1024 pixels)
iii) optical or mechanical mouse and keyboard;
iv) no dedicated hardware;
v) video hard copy unit, laser printer, external disk memory; quarter-inch cartridge tape drive, ethernet board
vi) scalable performance by transputer networks;
vii) "low-cost";
viii) portable software.

3 I.S.G. Technology Inc., Richmond House, Bath Road, Newbury, Berks. RG13 1QY England.

4 Philips Medical Systems, the Netherlands.

Optional:

ix) display with High Definition Television (HDTV) video standard (1920x1280 pixels).

2.4 Functional requirements

The following functional requirements must be satisfied:

i) Unix-based operating system, C-programming language

0ii) menu-driven man-machine interface , X-windows, MOTIFF (Wedler (1989));

iii) instructive error reporting;

iv) voxel data-set rendering (including data clipping) from arbitrary viewpoint by:

- parallel projection
- perspective projection
- depth shading
- voxel data read-out
- layer view
- wire frame
- transparent view
- solid modelling (surface rendering)
- combination of different rendering techniques

v) hidden surface elimination;

vi) selection of rectangular volume-of-interest;

vii) interactive visualisation by:

- window-width and window-level setting
- rotation and translation
- zoom
- pan

iix) 2-D, 3-D and 4-D (3-D series) image processing, including:

- noise reduction
- edge enhancement
- smoothing
- geometric distortion correction
- correction for transfer function
- knowledge-based image segmentation
- multi-resolution segmentation

ix) 2-D, 3-D and 4-D (3-series) object recognition, including:
- multiple modality confirmation
- knowledge-based reasoning

x) multiple image, text and graphics windows simultaneously.

2.5 Spin-in

A prototype, reconfigurable, transputer-based computer system for voxel data processing is already available (Huiskamp and van Lieshout (1989, 1990), Huiskamp (1991)). This system is capable of voxel visualisation including:

i) hidden surface elimination (Z-buffering, Painters algorithm);
ii) front view rendering;
iii) depth shading;
iv) voxel value integrated display;
v) layer display.

The voxel processing system utilises data parallelism rather than algorithmic parallelism, which makes it scalable from the hardware point of view (Huiskamp (1991)). This prototype voxel processing system is suitable as a point of departure.

The concept of computer-assisted radiotherapy planning (Wernet et al. (1987), Lipinski et al. (1987)) and computer-assisted stereotactic (neuro-) surgery planning and robot control (Doll et al. (1987), Kwoh et al. (1987)) have been demonstrated to be feasible.

2.6 Spin-off

High performance image interpretation and visualisation find not only applications in medicine. It may find applications in:

i) Confocal Laser Scanning Microscopy (CLSM) (see Huiskamp (1991));
ii) 3-D geophysics.

3 HIGH PERFORMANCE COMPUTING

3.1 Introduction

The industrial development and exploitation of information technology have greatly enhanced human capabilities and knowledge. The application of information technology has led to major breakthroughs in industrial and commercial competitiveness, scientific knowledge and the quality of life. The leading edge of information technology has been the pursuit of faster and more powerful computing techniques, enhanced by their interconnection via networks. Recent technological developments promise quantitative and qualitative changes in performance that could permit information technology to address as yet unresolved fundamental problems and to contribute improvements of industrial competitiveness.

Computing performance evolved rapidly and led, during the 1970's and 1980's, to super computers using a few, very fast processors (each currently able to sustain a performance of up to one thousand million operations per second) at a cost of millions of ECU's per system. At the same time, specialised users developed very high performance computing techniques (e.g., radar data processing) embedded in operational systems.

Between now and the year 2,000 this evolution is expected to become a revolution. The advent of a novel generation of parallel computers, based on the principle of many processors (up to a thousand) working together, will simultaneously allow an increase in performance of super computers by a factor 1,000 or more (one million million operations per second is considered feasible) and permit high performance computing to be embedded in new products and systems. At the same time, new software methods and improved computational models will result in a greater flexibility in adapting these computational resources to the needs and means of users (CEC (1992)).

3.2 Parallel processing

Computer applications tend to need increasing amounts of processing capacities. Single processor systems are reaching the limits of performance improvements. It is obvious that using more processors running in parallel could, at least in principle, provide unlimited power. Most existing multi-processor systems use a common communications channel (the bus) for interconnections.

With a growing number of processors the bus capacity becomes a bottle-neck for system performance. Communication bandwidth of the network must be increased also when processors are added. Providing processors with direct connections for all data exchange will supply increased bandwidth.

Several classes of multi-processor systems have been defined (Furht (1989)):

i) Single Instruction Multiple Data (SIMD). Each processor in the network will execute the same instruction (synchronously) on different data. Array processors fall in this class. SIMD is applied in, e.g., image processing where each processor performs the same (filter) operation on a different part of the image.
ii) Multiple Instruction Multiple Data (MIMD). Processors can all be running different programs, sending results to others when they have finished. MIMD is applied in, e.g., pipelined systems or multi-user applications.

Many existing sequential programs could benefit from being able to perform more than one action at a time. It is, however, generally not trivial to implement a parallel program on a network processor. Problems arising include:

i) decomposition of the problem into a number of processes running in parallel;
ii) allocation of processes to processors and selection of the network topology,
iii) load-balancing of the processors;
iv) distribution of the data over the processors;
v) efficient inter-processor communication;
vi) synchronisation of processors;
vii) debugging the software implementation.

3.3 Artificial Neural Networks

Artificial Neural Networks (ANN) are relatively new computing systems whose architecture is made of a massive number of densely interconnected simple analog processing elements. The processing is done in parallel either in a synchronous or asynchronous mode. The architecture of ANN is modelled after the human nervous system with some unique processing capabilities which are not found in the conventional, sequential computing system. One such processing task in which the ANN exels is in the area of pattern recognition. All reported ANN architectures have used a specific structure, known as generalised perceptrons (GP) or back propagation networks

(BPN). These networks use a training set very similar to the conventional supervised methods, with the exception that no a priori probabilistic knowledge is required (similar to the conventional nonparametric methods) (Lippmann (1987)). Neural networks have found applications in control systems as well (Antsaklis (1992)).

Another neural architecture which has attracted considerable attention in the recent past was proposed by Hopfield (Hopfield (1982)).This type of network has been proposed for the unsupervised classification of patterns: images modelled as a Markov random field can be assigned region labels or pixel labels by minimising the expected percentage of misclassified pixels on a Hopfield network (Rignot and Chellapa (1991)). With a Hopfield network an energy function can be minimised. An extensive overview of the progress achieved in supervised neural networks can be found in Hush and Horne (1993).

3.4 European Industry Initiative Ei³ for High Performance Computing

The European Industry Initiative (Ei³) exists to act as a forum for industrial and commercial users of HPC to discuss their requirements and make recommendations to various national and supranational bodies working in HPC and related areas. Initially, Ei³ aims to assist the CEC in the definition of, and launching process for, the HPC programme with a clear industry perspective of the field and its needs to maintain competitiveness in the global market. Although the position of the European industry is fairly strong in particular areas to HPC, we badly need a broad HPC applications industry and the necessary infrastructure. Ei³ as an applications-driven industrial grouping strives to ensure that this aim is realised through the synergy between Ei³, its associates, the CEC and other national and supranational bodies.

Ei³ aims in particular at:

i) providing a platform for interested parties to discuss their HPC needs and to focus their requirements;
ii) developing an industrial HPC strategy and programme by bringing together application developers and technology providers. Ei³ believes that a big thrust will come from innovative industrial application areas in particular the real time arena;
iii) fostering standardisation wherever possible, the actual lack of it being a major obstacle to a parallel computing industry;

iv) identifying the needs for training, technology transfer and other supporting infrastructure for HPC;
v) assisting the CEC in defining and launching HPC as a Large Scale Targeted Programme that will enable Europe to play a prominent role as a solutions' provider on the world stage.

Ei^3 is as open as possible without sacrificing the overall goals and momentum of the initiative. The working groups in Ei^3 are:
i) Ei^3 working group on applications;
i) Ei^3 working group on software architecture;
iii) Ei^3 working group on hardware and architectures;
iv) Ei^3 working group on algorithms and methods.

The Physics and Electronics Laboratory TNO participates in the European Industry Initiative Ei^3.

3.5 Information Technology , Telecommunication and Telematics Initiative

In recognition of the increasingly important role Information Technology , Telecommunication and Telematics (IT&T) are playing in modern society, TNO's management has decided to launch a major new IT&T initiative. This initiative is intended to make TNO's broad range of IT&T skills and expertise more accessible to potential clients. Not only is TNO anxious to foster greater synergy in IT&T developments, but it is also keen to extend the scope of such activities.
TNO has identified nine areas, which are already part of its core business, that intends to target in its new IT&T initiative. These include :
i) Virtual Reality;
ii) Process Control;
iii) Product Data Exchange;
iv) Document Information Systems;
v) Traffic and Transport;
vi) Training and Simulation;
vii) High Performance Computing;
viii) Human Factors Engineering;
ix) Signal Processing.

In developing and applying IT&T technologies in the nine target areas, TNO will continue to utilize its wide pool of knowledge and expertise in related fields such as materials science,

structural engineering, applied physics and process technology (excerpt from TNO Newsletter Applied Research, April 1993).

3.6 TNO-FEL High Performance Computing

TNO-FEL High Performance Computing (HPC) is a centre of expertise for information technology fully exploiting HPC. TNO-FEL provides research, development, engineering and consultancy services to governments and industries. Clients are assisted in solving complex problems and challenging technical problems and technological innovation. TNO-FEL regards HPC technology as an area of strategic importance. Currently, to develop leading edge technology, TNO-FEL actively participates in national and international Research and Technology Programmes (ESPRIT, EUCLID).

TNO-FEL has invested significantly in applying HPC in 2-D and 3-D (medical) Computer Vision, 3-D real-time simulation and visualisation (image generation and virtual environments), image reconstruction and signal processing and has now obtained an internationally recognised position in these fields. TNO-FEL has initiated both a National and a European Industrial Initiative for High Performance Computing. HPC at TNO-FEL includes hardware and software technology and system applications development towards quality standards like ISO 9000. TNO-FEL has developed (hardware and software) a multi-processor, scalable and configurable architecture (currently with 24 i860 processors) with dual communication channels (>100MBytes/s each) for image generation and voxel data visualisation. For image generation, image processing and visualisation purposes, TNO-FEL uses also four transputer-based systems with 6, 10 and 2x21 T805-processors and a communication channel with 120MBytes/s capacity, and also a scalable, electronically configurable transputer-based multicluster (64 times T805) with graphics boards. For visualisations with real-time virtual reality (VR) performance TNO-FEL uses a hybrid system with both T805 transputers and i860 processors with advanced VR-helmet and control devices. (All T805 transputers will be replaced by T9000 transputers as soon as this processor becomes available.) TNO-FEL has initiated a European project for the industrial development of a training and simulation system for Minimal Access Surgery, and is working on a national industrial HPC utilisation initiative for Medical Radiation Applications.

4 COMPUTER SYSTEMS ORGANISATION

This chapter contains an introductory overview of the organisation of computer systems which may be applied to HIPMI^{2}S. It does by no means intent to define the hardware configuration of HIPMI^{2}S.

4.1 System architectures

A computer system can be constructed with the use of modules, including:
i) host computer;
ii) control processors;
iii) graphics processor;
iv) frame grabber;
v) transputers.

The host computer is the main computing module in the architecture. It may be a Personal Computer (PC) system, advanced workstation, mini or main frame computer, and it hosts the operating system.
A control processor, or controller in short, services the interface between the host computer and a peripheral device. When a topology network of transputers is connected to the host computer for additional computing power, a controller is used to give the transputer network slave instructions. The network informs the controller about its status and the status of the task that has been performed. There is also a controller required to interface with the graphics processor.

A graphics processor is an additional, dedicated processor for graphics purposes. It accepts commands from the (graphics) controller. Usually, a graphics processor is added as a server, implying that it continuously expects input from the controller.

A frame grabber, with corresponding controller, is usually equipped with video memory and allows for the digitisation of a video signal (analog-to-digital conversion). There are a lot of different types available, ranging from simple grabbing boards to multi-colour overlay grabbing and display boards.

There are various types of transputers available, differing in the amount of 'on-board' memory, the

number of input-output links and the number of bits the floating point processor.
Depending on the computational task to be performed, a computer architecture can be composed such that the (performance) requirements can be satisfied. To decide on the architecture, a system specification methodology can be followed.

4.2 System specification methodologies

A hard- and software system can be designed following a structured design methodology. Thereto, functional black boxes are defined which are connected to obtain a hierarchical, functional system. The interconnections are attributed with data and control streams. A graphic display of the black boxes and interconnections is called a structure chart, and hence shows the organisation of the complete system. The structure chart serves as a specification for system implementators and can be used to gauge the functionality and quality of the system.

Modules are specified by a description, for software systems called a pseudo code, including i) the module name; ii) its purpose; iii) the modules it uses; iv) its input/output specifications and v) a list of functional details, including error handling.

An interconnection is a measure of the interdependence between two modules. There should be a minimum of interconnections by elimination of unnecessary relationships between modules, reduction of the number of required connections and easing the tightness of necessary relationships. There exist three types of interconnections: i) connection by parameters, ii) connection by a globally accessible data area and iii) connection by directly connecting the internals of modules.

A structured specification should consist of i) a data flow diagram; ii) a data dictionary; iii) state-transition diagrams, iv) decision trees; v) decision tables and vi) an informational model. Page-Jones (1988) describes these items as follows.

A structured data flow diagram shows the active components of the system and the data interfaces between them. It is used to partition a system while the system's structuredness, desired qualities, conciseness and degree of partitioning can be concluded from this diagram.

A structured data dictionary is an analysis tool that primarily records the information content of

data and includes physical format details of data only as an addendum. It contains the definition of all data mentioned in all diagrams.

A state-transition diagram shows the various states of a system and the relationships between these states. Decision making is the basis of transitioning from one state to another.

A decision tree and decision table explicitly show the decision making process.

The specification process must be verified using structured walkthroughs. Guidelines therefore can be found in Page-Jones (1988) and Yourdon (1986).

Recently, object-oriented analysis and design methodologies became in fashion. A comparison of techniques and critiques can be found in Fichman and Kemerer (1992).

4.3 Single data stream architectures

A single data stream architecture allows for the sequential processing of data according to the program code or the user instructions.

4.4 Multiple data stream architectures

Duncan (1990) is one of the many authors, who distinguish parallel architectures, vector processors, SIMD architectures, processor arrays, associative memory processor architectures, systolic architectures and wave front architectures. He describes them as follows.

Parallel architectures are high-level frameworks for the development of parallel programming solutions by providing multiple processors, whether simple or complex, that cooperate to solve problems through concurrent execution.

Vector processor architectures are characterised by multiple, pipelined functional units, which implement arithmic and Boolean operations for both vectors and scalars and which operate concurrently (synchronous architecture).

SIMD architectures consist of a central control unit, multiple processors with local memory, and an interconnection network for either processor-to-processor or processor-to-memory

communications.

MIMD architectures employ multiple processors that can execute independent instruction streams using local data: they support parallel solutions that require processors to operate in a largely autonomous fashion (asynchronous computers, characterised by decentralised hardware control). Basically, there exist 4 topologies:

i) *ring topologies*: most appropriate for a small number of processors executing algorithms not dominated by data communications;
ii) *mesh topologies*: each of the communication lines is connected to its 4 immediate neighbours (also called lattice topology);
iii) *tree topology architectures*: constructed to support divide-and-conquer algorithms for searching and sorting, image processing algorithms, and data flow reduction programming applications;
iv) *hypercube topology*: most appropriate for developing "scalable" architectures that support the performance requirements of 3-D scientific applications.

These SIMD architectures can be configured by programmable switches that allow users to select a logical topology matching application communication patterns.

Processor array architectures are useful for large scale scientific calculations, such as image processing when structured for numerical SIMD execution.

Associative memory processor architectures are distinctive types of SIMD architecture that use special comparison logic to access stored data in parallel according to its contents. A program controller, usually a serial computer, reads and executes instructions, invoking a specialised array controller when associative memory instructions are encountered. Special registers enable the program controller and associative memory to share data.

Systolic architectures, or systolic arrays, are pipelined multiprocessors in which data is pulsed in rhythmic fashion (synchronous control) from memory and through a network of processors before returning to memory.

Wave front architectures make use of asynchronous control, while data are transported through the networking, evoking processes at their arrival.

4.5 Computer-communication networks

Distributed computing is the loosest form of parallelism, in which parts of a problem are divided among various nodes and there is relatively little communication once processing begins.
A communication method is like packet-switching: every processor in the system has an address, and routing information in a message guides it through the network, sometimes through intervening processors, to its destination. Generally, the routing of messages is explicitly worked out by the programmer, possibly with the assistance of various software tools, as the program is written. Message passing is the most popular programming model for massively parallel processors (Zorpette (1992)).

4.6 System maintenance

Mutatis mutandis <u>Section 5.5</u>: System maintenance.

5 SOFTWARE SYSTEM ORGANISATION

A software system is defined as the integration of software code which runs on the hardware system. The organisation of this software system may be dependent or to a certain level independent of the hardware system. Therefore, all that applies to the system specification methodologies (Section 4.2) applies to the software system organisation. In this chapter programming techniques and software engineering techniques are discussed. With these techniques a software system can be defined. Next, programming languages and operating systems are discussed.

5.1 Programming techniques

Programming techniques can be distinguished into three catagories:

i) process-oriented programming;
ii) object-based programming;
iii) object-oriented programming.

Process-orientated programming allows for the design of systems in which the focus is on a process to be modeled. This has been the traditional technique to programming up to the early 1980's.

Object-oriented programming aims at information hiding, abstraction, dynamic binding and inheritance of object features (Bihari and Gopinath (1992) and Rine and Bhargava (1992)).

Object-based programming is like object-oriented programming, with the exception that it does not support inheritance. It does support data and program abstraction, generic types and operator overloading.

5.2 Software engineering

See Section 4.2: System specification methodologies, especially applied to software systems.

5.3 Programming languages

A parallel programming language can provide different levels of (hardware) architecture independence, depending on how much of the underlying architecture is hidden from the

programmer. There 5 main levels at which independence can be enforced (Webb (1992)):

i) the processor architecture;
ii) the array size;
iii) the array topology;
iv) the interprocessor communication;
v) the process management.

Process-oriented programming languages.

Software code running on MIMD architectures may be implemented in any programming language (Pascal, C, Fortran, etc.). However, these programming languages do not facilitate communicational aids. A programming language with the ability to have control over the communication is OCCAM 2 (Hoare (1988)). OCCAM supplies the highest possible performance, but is not easily ported to other computer configurations. The C-programming language, however, makes porting of code more easy. Besides, the C-programming language is more or less accepted as an industry standard for programming.

Object-oriented programming languages

Recently, programming langueges became available that support the object-oriented programming concept. These languages include :

i) FLEX (Kenny and Lin (1991));
ii) RTC++ (Ishikawa et al. (1992));
iii) RIPE (Miller and Lennox (1988));
iv) CHAOS (Schwan et al. (1987)).

'Older' languages are, e.g., Smalltalk 80 and C++. In the object-oriented model, the entire world is made up of two types of entities: objects and messages. With this model the understandability, adaptability and code reusability are increased, while it carries properties like information hiding, abstraction, dynamic binding and inheritance of object features (Bihari and Gopinath (1992) and Rine and Bhargava (1992)).

Objects include both software and physical entities. Software objects encapsulate data and provide units of code called methods for accessing data. Each object is assigned a unique name for identification purposes: other objects can address it with this name. Objects communicate by

sending and receiving messages.

Messages are addressed to the receiving object and contains the name of a specific method of the recieving object that is to be executed, along with parameters such as names of other objects. An object can manipulate another object's encapsulated data using the message.

5.4 Operating Systems

HELIOS has recently been developed and becomes (more or less) accepted as an industry standard Operating System (OS) for transputer networks. HELIOS provides a UNIX-like 'look and feel' programming environment for the C-programming language. It runs on both Personal Computer systems and UNIX-based workstations. An excellent graphics output and a menu-controlled user-interface can be provided via calls to the HELIOS-supported X-window library.

5.5 System maintenance

Maintenance is usually a part of the software life cycle delegated to low-level programmers. Planning for maintenance should take place concurrently with development. A standard for software maintenance will provide powerful help to those who prefer to keep large and complicated software systems operational irrespective of their age. The IEEE P1219 Working Group[5] is creating such a standard to address the problem of software maintenance that faces all corporations. This standard is expected to be adopted early 1993 (Vera-Edelstein and Mamone (1992)).

5 Contact persons: D. Vera Edelstein and Salvatore Mamone, NYNEX Science and Technology Inc., 500 Westchester Avenue, White Plains, NY 10604, USA.

6 DATA

6.1 Image formats

The American College of Radiology (ACR) and the National Electrical Manufacturers Association (NEMA) prepared image formats and data communication formats (ACR/NEMA (1988)). These standards are more or less accepted by a large number of suppliers of medical imaging systems (Herforth et al. (1989)). Consequently, these standards should be followed. For this standard and other ones, see de Moor et al. (1993).

6.2 Data compaction and compression

Data compaction and data compression aim at obtaining an efficient representation of (image) data for strorage and transmission purposes. There are two types of compression techniques:
i) irreversible (lossy, noisy or information reducing compression);
ii) reversible (lossless, error free or information preserving compression).

Highest data reduction is obtained with irreversible compression at the costs of loosing data. Due to legal aspects in medical imaging, irreversible data compression is not in all countries allowed. In some applications reversible data compression is prefered over irreversible compression since errors may be enhanced during image post processing.

Data compression algorithms can be characterised by:
i) bit rate;
ii) encoding/decoding time;
iii) robustness.

Roos (1991) concluded for reversible intraframe compression, that the Laplacian Pyramid, Walsh-Hadamard Transform, Sequential Transform, Discrete Cosine Transform and Subband Coding are inferior techniques compared with (Adaptive) Dynamic Pulse Code Correlation and the Hierarchical Decorrelation Method based on interpolation. According to Roos, the last technique has the best performance, it is simple, it does not use parameters and has a low sensitivity to noise and channel errors.
For reversible medical image compression, Roos (1991) concluded that both the Huffmann and

the arithmic coding outperform the Lempel-Ziv coding. Model-based static Huffmann coding performs optimally for both 8-bit and 12-bit radiological and nuclear images. An efficient hierarchical method for reversible image compression is described by Viergever and Roos (1993).

7 DATABASE MANAGEMENT

Mass data handling and data storage require advanced database management systems. Here, we distinguish a medical image database system (Section 7.1) from a logical database system (Section 7.2). The first is used for images, the latter for image objects and object features.

7.1 Medical Image Database System

Database management supports the storage, retrieval, presentation and interpretation of medical images. The medical image database system can be linked to the logical database system, as has been demonstrated by Orphanoudakis et al. (1989).

7.2 Logical Database System

A logical database system supports image feature extraction, image content representation and organisation of stored information, search and retrieval strategies and user interfaces. To date, a general methodology for the design of databases has not been developed. There are many concepts for databases. To allow data representations at various levels of abstraction, the concepts of multidatabases may deliver prospects. These include (Bright et al. (1992)):

i) distributed databases;
ii) global schema databases;
iii) federated databases;
iv) multidatabase language systems;
v) homogeneous multidatabase language system;
vi) interoperable systems.

Each multidatabase concept has its novelties in issues like:

i) site autonomy;
ii) data representation (names, formats, structures, conflicts, missing data);
iii) contraints;
iv) processing;
v) concurrency control and vi) security.

8 IMAGE PROCESSING TECHNIQUES

This chapter contains various aspects of image processing techniques. We do not aim at completeness but at presenting a concise overview.

8.1 Digitisation

When an image is to be processed by a computer, it is often described as a matrix, or some other data structure. This conversion requires 3 steps:

i) scanning,;
ii) sampling;
iii) quantitization.

Scanning is the process to acquire a signal from a sensor which is to form an image of a scene in a general sense.
Sampling is required in order to convert the signal into a finite set of numbers: sampling is the selection of a set of discrete points in the continuum of time and space. Only the values of the signal at those points will be used for further processing. The sampling frequency must satisfy Shannon's sampling theorem (e.g., Pavlidis (1982)) to guarantee that the signal can be reconstructed from the finite set of samples. However, there is often a need to oversampling, depending on the reconstruction algorithm used. If the sampling interval does not satisfy Shannon's sampling theorem, then a distortion of the signal spectrum occurs that is known as aliasing: a high frequency signal appears as a low frequency signal after sampling at too low a rate.
Quantitization is the process of representing the signal values by a finite number of bits, and can be considered to be a mapping from real numbers into a range of integers. Since the amount of bits is often insufficient to represent the real numbers, the differences appear as quantitization noise.

The process of scanning, sampling and quantitization is referred to as digitisation.

8.2 Enhancement

Image data often need enhancement of characteristics and correction for distortions introduced during the imaging process. Examples of image enhancement techniques are:

i) grayscale manipulation (stretching);
ii) histogram equalisation (contrast enhancement);
iii) sharpening (edge enhancement);
iv) smoothing (blurring).

Advanced image filtering techniques are available to accomplish image enhancement.

8.3 Restoration

Images are produced in order to record or display useful information. Due to imperfections in the image formation process (a nonlinear modulation transfer function (MTF) of the imaging chain), however, the recorded images often represent a degraded version of the original scene. Although the degradations may have many causes, two types of degradation are usually dominant: blurring and noise. The field of image identification and restoration is concerned with the problem of undoing the effects of imperfections in the image formation process in order to facilitate the (human) interpretation or further processing (e.g., analysis) of the recorded images. More specifically, the goal of image identification is to estimate the properties of the imperfect imaging system (blur) from the observed degraded image, together with some (statistical) characteristics of the noise and the original (uncorrupted) image. On the basis of these properties, the image restoration process computes an estimate of the original image (Lagendijk (1990)). In medicine, these techniques can be applied to reduce cardiac and respiratory motion artefacts in image data (e.g., Atalar and Onural (1991)).

The correction for distortions introduced by the imaging system is often necessary, especially when object features are to be extracted from the image data. Image distortion can be removed with available techniques in the field of stochastic restoration, including Bayesian methods, Wiener filtering and Kalman filtering, the field of algebraic restoration and iterative methods (Lagendijk (1990), Lim (1990), Kaufman and Tekalp (1991)).

Image enhancement and image restoration are the first step in image analysis.

8.4 Reconstruction

Image reconstruction is directed towards the (re-)construction of, usually cross-sectional, images from projection data (Dumay (1992)). Algorithms for reconstruction from emission, transmission and reflection data are widely available (Herman (1980), Kak and Slaney (1987), Natterer (1986)). Recently, advanced iterative algorithms in the field of image reconstruction became available (van Dijke (1992)), including statistical approaches (e.g., Liang et al. (1989)), Ollinger (1990)).

8.5 Segmentation

The segmentation of an image into single objects and their mutual relationships is the second step in image analysis. Image segmentation is directed towards edge detection and partitioning the image into regions which are homogeneous according to some predefined criteria. The success of an image segmentation procedure can usually only be evaluated at a higher level of data abstraction.

There are roughly three types of image segmentation approaches:

i) segmentation by filtering and thresholding (Sahoo et al. (1988), Zhang and Gerbrands (1992));
ii) rule-based image segmentation (Levine and Nazif (1985), Smets (1990));
iii) employing pyramidal structures (Tanimoto (1983)) and hyperstacks (Jackway (1992)).

These techniques can be applied to various types of images, though dedicated techniques are available for segmenting noisy images (Gerbrands (1988), Dumay et al. (1992)). De Graaf et al. (1992) elaborated on a method to evaluate the success of image segmentation methods.

8.6 Feature extraction

Extraction of features like invariance, moments, projections, size and shape, and texture follows the segmentation level. At present, a large number of techniques are available (Simon (1988)), including those making use of parallel computing techniques (Burkhardt et al. (1990)). Recently, Salden et al. (1992) presented a new method of multi-resolution image analysis that gives the most concise set of local orthogonal invariant features of 2-dimensional input images. Reiss (1992) used tensors to generate algebraic invariance in 2-D and 3-D images, and showed that

these features are much more robust than affine invariant Fourier descriptors.

8.7 Scene analysis

Image understanding by computer techniques is a process which proceeds from raw digital images to a symbolic description of the contents of the image scene. Essentially, image understanding by computer can be considered as the extraction of meaningful entities or the confirmation of the absence of some meaningful entities within the given image(s), as well as giving a description of their interrelationships in the context of the original scene, which is represented by the image(s). Scene analysis is the final stage of an image understanding system and can be found at the highest level of abstraction. At this level, domain knowledge must be included (e.g., Cheng (1990)).

8.8 Data fusion/registration

Data fusion, or registration, concerns the matchting of data colected from different scanning systems. It involves transformations to map one image reference system onto another system. Van den Elsen et al. (1993) distinguish two types of methods, i.e., intrinsic and extrinsic transformation methods. Intrinsic methods make use of patient-related properties (pixel or voxel values, anatomical landmark points, geometrical features, administered constrast dye, etc.), while extrinic methods make use of, e.g., head-mounted frames or skin markers.

9 PATTERN RECOGNITION

This chapter contains an introductory and definitely incomplete overview of topics related to pattern recognition. Pattern recognition can be carried out by either classification of samples on the basis of sample features (supervised) or clustering of samples on the basis of a (unsupervised) grouping criterion.

9.1 Decision models

At present, there are some distinct decision models known, including the Bayesian decision theory. Bayesian decision theory is a fundamental statistical approach to the problem of patter classification. This approach is based on the assumption that the decision problem is posed in probabilistic terms, and that all the relevant probability values are known (Duda and Hart (1973)).

The disadvantage of supervised methods is the need for the generation of training sets and the associated human interaction and that of the unsupervised methods is its ignorance of the relationships between different objects and a tendency to generate too many clusters or groupings which can be misleading.

Advanced models in the field of fuzzy set theory are available (Pal and Dutta Majumder (1987)), while pattern recognition by employing artificial neural networks is described in some more detail in Section 3.3.

9.2 Design methodology

Classifier design and evaluation, feature evaluation and selection, and pattern analysis are needed in the exploratory data analysis. Design methodologies can be found in text- and handbooks (e.g., Duda and Hart (1973)).

9.3 Clustering techniques

The design and evaluation of clustering or grouping techniques is described in textbooks like Coolpy and Lohnes (1971), Fukunaga (1972), Anderberg (1973), Clifford and Stephenson (1975), Hartigan (1975), Everitt (1978) and Dubes and Jain (1981).

10 ANALYSIS OF ALGORITHMS AND COMPLEXITY

Image Enhancement

Perona and Malik (1987) and Gerig et al. (1992) described nonlinear anisotropic filtering of MRI data in scale space and claim that object contours, boundaries between different tissues and small structures such as vessels are not only preserved, but even enhanced: the filtered images appeared clearer and boundaries were much better defined, leading to an improved differentiation of adjacent regions of similar intensity characteristics. The algorithm is suitable for parallel implementation.

Image Segmentation

Amartur et al. (1992) described a preliminary study to segment multicontrast MR images with the use of a Hopfield neural network. They applied a modification to the energy function suggested by Hopfield (1982) and proved its correctness. The objective was to assign N pixels of P features to M classes such that the assignment of the pixels minimises a criterion function for which a metric measure between a pixel and a class or a nonsimilarity measure between a pixel and the other classes was chosen. The neural architecture consisted of a grid of NxM neurons with each column representing a class and each row representing a pixel. The system inputs are initialised to random values (mean 0, standard deviation about mean 0.1) The network was said to have reached convergence if all neurons have negligible input-output activity. Good results were obtained from T2-weighted and proton density-weighted images: a good differentiation between the gray and white matter was achieved. This work is in progress.

Soltanian-Zadeh et al. (1992) evaluated the performance of several filters applied to MRI scene sequences for image enhancement and segmentation. They compared the signal-to-noise ration, contrast-to-noise ratio, segmentation of a desired feature and the correction for the partial volume effect from the various filters. They concluded that the eigenimage filter (Soltanian-Zadeh et al. (1990)) performed best with respect to the segmentation of a desired feature and the correction to the partial volume effect.

Choi et al. (1991) introduced a statistical image model which allows mixture of multiple classes within a voxel. This model seems well-suited for medical images including MRI, in which many

voxels represent mixtures of multiple tissues. Since the method depends on the assumption that the structures of interest are somewhat larger than single pixels, modifications may be required in order to accurately estimate the extent of smaller pathologic lesions in the brain, such as small infarcts. Iterative reestimation of the mean of each class appeared to provide a moderate improvement in performance at little additional computational cost. Improvements in accuracy would be expected to result from increasing the number of measurement channels and by relating the assumption that within-class variations in signal intensity are negligible in comparison to measurement noise. The algorithm is inherently parallel.

Zijdenbos et al. (1992) described a very simple technique to automatically extract the intracranial cavity on transverse MR brain images. They spoke of a robust algorithm, though the contours were automatically detected successfully in only 70% of 76 slices in 4 volumes. With user-interaction the success rate increased to 91%. The limited success of the automatic version was attributed to the partial volume effect, which blurred the tissue transitions.
Best and most reliable methods for image segmentation are those involving multiscale approaches (Choi et al. (1991), Ueda and Suzuki (1993), and Mokhtarian and Mackworth (1986)).

Data Fusion

Clarysse et al. (1991) described the mathematics involved with frameless matching of MRI and X-ray images under stereotactic conditions. The accuracy and precision of localisation is claimed to be sufficient for computer-assisted interventions. This has been demonstrated on 24 patients.

Visualisation

Valentino (1990) and Valentino et al. (1991) described a procedure for combining and visualising complementary structural and functional information from MRI and PET. Images of the human brain were obtained and correlated to form three-dimensional volumes of image data. Volume rendering and solid-texturing concepts were combined to develop a new volume imaging technique for "volume texture-mapping", brain glucose metabolism (from PET) onto brain anatomy (from MRI). A consice overview of visualisation methods can be found in Barillot (1993).

11 EVALUATION AND DEMONSTRATION

11.1 Evaluation of techniques

Evaluation of developed techniques should be carried out in three steps:

i) computer-simulation studies;
ii) realistic phantom studies;
iii) real (patient) studies.

Computer-simulation studies are required in order to implement a demonstrator. Studies based on the data acquired from a realistic (patient) model (phantom) are necessary to demonstrate the potential of HIPMI^{2}S and to obtain an impression of the sensitivity (accuracy) and specificity (precision) of the system. These studies are also necessary to prove the stability of the system under parameter control. Real (patient) studies are required in order to have the system accepted in the field of medicine.

11.2 Demonstration

A demonstration system consists of the complete hardware configuration and the complete software configuration, applied to data from a computer-simulation, realistic phantom study and real patient study.

12 MANAGEMENT OF COMPUTING AND INFORMATION

The management task force and resources play a key role in bringing a project to a success. In this chapter, some of the goals and the constraints are defined and techniques to reach the goals within the constraints are elaborated upon.

12.1 Project management

The management team consists of the line management (head of a department), division management (section head) and assignment providers. They appoint a project manager, who is given the responsibility and autherisation of:

i) the complete project realisation, including
   - a detailed system analysis
   - system design
   - system development;

ii) milestone) reporting to the management team;

iii) changes in the project realisation strategy;

iv) financial allocations and budget control;

v) negotiating in conflicting situations;

vi) project controlling to support descision making by the management team.

In agreement with the project manager, the management team assigns personell from the various disciplines, departments and sections to the project (matrix organisation).

12.2 People management

Personell assigned to a project work together with the project manager. The people are carefully selected by the management team in collaboration with the project manager, who defines the qualities required. The project manager looks after appropriate training of personell whenever required.

Each person assigned to a project reports weekly to the project manager on i) progress, ii) problems and iii) plans for the next week. The project manager and the assigned persons meet weekly to discuss these items and to take action wherever required. These discussions should take place in an atmosphere of confidence and trust.

12.3 Installation management

The detailed system analysis results in:

i) benchmark definition,

while the system design needs:

ii) computer selection and configuration

and the system development need:

iii) computer equipment management;

iv) performance and usage management.

These four items fix the limits of the installation management.

12.4 Financial management

The financial management covers i) pricing and ii) resource allocation. A priori financial management is a prime responsibility of the management team. In the course of the project, these topics of financial management should be in the responsibility of the project manager.

12.5 Software management

In collaboration with the project team the project manager decides on:

i) the software development methodology;

ii) software maintenance;

iii) software selection.

In general, however, constraints must be satisfied. These include the policy of the department and the user requirements.

A software development methodology is of utmost importance when the project team consists of more than two persons. By consequently following one single methodology, a consistent and well-documented software package will be delivered.

Software maintanance is in general overlooked. However, with an expected ongoing evolution in hardware and software implementation technology, decisions should be made with respect to the

portability and generity of software systems. The profits of portability and generity must be in equilibrium with performance requirements.

Commercially available software that suit with the specified requirements should be applied when its quality has been confirmed and profit is evident.

12.6 System management

A consistent system can only exist when the quality of the individual modules is assured. To see to that, a system manager should be appointed, who also has the task of system integration.

12.7 Legal aspects

It is not the FEL-TNO policy to apply for a patent at any cost. There where possibilities arise in the interest of FEL-TNO and/or its collaborating partners a careful consideration will be carried out for each opportunity. Copy rights and document classifications will be handled conform the FEL-TNO regulations and agreements.

13 MARKET APPROACH

13.1 Market pull

Each hospital in the Netherlands will be equipped with MR imaging facilities by the year 2000. At this moment about 6600 MR imaging systems are installed worldwide by the main manufacturers Siemens, General Electric and Toshiba (Dakins (1993)). The users of those systems need facilities to interactively visualise, manipulate and analyse 3D images. Mainly due to a lack of computer power the images are presented on a slice-by-slice basis. High Performance Computing technology may solve their problems. However, suppliers of MR systems are spending less on Research and Development (Dakins (1993)) leaving opportunities to R&D companies such as TNO.

Radiotreatment planning is (usually) carried out with the support of PC-based computer systems. As a result of the limited available computer power a single planning session may take up to 8 hours. High Performance Computing technology can be utilised to reduce the time for planning and to apply patient- and user-friendly planning methods on CT or MR images using interactive visualisation and extraction tools. The market, however, is expected to be narrow (less than 10 systems in the Netherlands and at most a few hundred worldwide).

Neurosurgery requires careful planning on the basis of CT or MR images. This can only be achieved reliably when visualisation and extraction tools are available. At present these planning procedures are carried out on powerful workstations limiting the time of the surgical intervention to about 24 hours. This time may be further reduced when High Performance Computing is applied.

Training and simulation in a virtual environment is gaining interest of the clinicians. This includes diagnosis (Ogle (1993)) and surgery (Satava (1992)). Especially training of Minimal Access Surgery in a virtual reality is expected to take a flight. A 1993 market survey carried out by Thomson-CSF suggests a market size for surgery training systems as large as for MR imaging systems! (see the ESPRIT III project proposal CLEOPATRA). Training systems are constructed round about an anatomical model, which should be extracted from CT and MR images with the aid of High Performance Computing tools for interactive visualisation and extraction of organs.

Triage, a decision protocol to assess the status of casualties in crisis or war situations, can be trained in a multi-media environment (Vossen (1993)). Such training systems are not only important for training military personnel but also for training personnel in trauma centres. In the Netherlands, each university hospital supports a trauma centre. Virtual reality, generated with High Performance Computing, may increase the realism of simulated casualty training sessions. An anatomical model required for triage should also be built with the aid of High Performance Computing tools for interactive visualisation and extraction of organs.

13.2 Technology push

MR and CT visualisation, manipulation and analysis, radiotreatment planning, neurosurgery, training and simulation for radiology, surgery and triage desperately need additional computer power for registration, visualisation and extraction purposes. HPC hard- and software modules should be developed for the industries following either of two approaches: i) contracting by a company, or; ii) PROGRAMMATISCHE BEDRIJFSGERICHTE ONDERSTEUNING VAN MEDISCHE STRALINGSTOEPASSINGEN (Dumay et al. (1993)). The first approach is company-driven, the latter is branch-driven aiming at forming a Nederlands Industrieel Initiatief to support each branch. Such an initiative should be taken by TNO and a choice of TNO-institutes should participate.

13.3 The role of TNO

The TNO Physics and Electronics Laboratory (TNO-FEL) excels in developing and applying High Performance Computing technology (see also Paragraph 3.6) There is a thorough understanding of applications in the 21 TNO-institutes, which can be made availble to a specific project. This understanding is based on TNO's maintenance of knowledge portfolios and a close relationship with the universities and industries in the Netherlands and Europe. The attractiveness for the industries lies in the understanding of both technology and applications within the same organisation. In a concerted action within the TNO-institutes, best results are persued in the interest of clients.

CONCLUSIONS

The objective of this report is describing a brief inventory of potential areas in medicine where High Performance Computing (parallel and distributed computing) technology is needed from an end-user's point of view. The potential areas are described in detail to give an understanding of what it is all about. The commonality in all these areas is image interpretation.
In this report we described an introduction to the field of medical imaging (Chapter 1) and the position of a High Performance Computing Medical Image Interpretation System (HIPMI^{2}S) therein (Chapter 2). The role of High Performance Computing (HPC), especially of the HPC Section at the Physics and Electronics Laboratory TNO, towards medical image interpretation was outlined in Chapter 3. We elaborated on computer systems organisation (Chapter 4), software system organisation (Chapter 5), data formats and standards (Chapter 6), database management (Chapter 7), image processing techniques (Chapter 8) and pattern recognition techniques (Chapter 9). In Chapter 10 we analysed some potential methods delivered by literature, and concluded that multi-scale approaches perform best for image registration and segmentation, while for visualisation purposes more or less standard techniques can be used. Evaluation and demonstration requirements are summarised in Chapter 11, and the management of computing and information is described in Chapter 12. A market approach by market pull, technology push is sketched in Chapter 13.

In medicine, two main areas can be distinguished, i.e., diagnosis and treatment. Diagnosis is applied in radiology (conventional x-ray imaging, computer tomography (CT), magnetic resonance imaging (MRI) and magnetic resonance angiography (MRA), angiography, arteriography, digital subtraction angiography (DSA), dual energy imaging and ultrasound techniques) and nuclear medicine (single photon emission computer tomography (SPECT) en positron emission tomography (PET)). In treatment can be named radiotherapy and surgical interventions like stereotactical (neuro-)surgery and minimal access surgery (MAS). With the introduction of computer systems in medicine, quantitative analyses of 2D images have been more or less accepted in the assessment of disease. Quantitative Computed Tomography (QCT), however, has not found its way to the clinics for routine use, and the same is about to happen to Quantitative Magnetic Resonance (QMR) despite the notion that all hospitals in the Netherlands will be equipped with MR imaging facilities by the year 2000. There are several reasons debt to this. From the technology point of view the main reason is the limited computer power made available to perform the huge number of instructions to visualise 3D images and to interactively

extract regions of interests from these images with acceptable performance. Hence, currently commercially available systems visualise and process 3D images on a 2D slice-by-slice basis. In literature many algorithms for image registration, image segmentation and image visualisation are available. All these algorithms have been demonstrated under laboratory conditions, neglecting their practical usability. With the advent of High Performance Computing, the utilisation of these algorithms in routine clinical practise may become feasible.

In this report we advocate and elaborate upon the development of HPC modules for image registration, segmentation and visualisation to the benefit of both the end users (medical specialists) and the manufacturing industries. Some of these modules may be developed as part of the "Smart Surgeon" of the ESPRIT III project CLEOPATRA. These modules may find application in all forementioned areas, especially in radiotherapy planning and training and simulation in Virtual Environments. TNO is about to initiate a Netherlands Industrial Initiative for Radiodiagnostics and Radiotherapy to define a development programme for some key companies in the health care industries (Dumay et al., (1993)). With the modules developed for the "Smart Surgeon" an anatomical model can be extracted from CT and MR images for triage training in a virtual environment (Dumay (1993)).

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REPORT DOCUMENTATION PAGE (MOD-NL)

1. DEFENSE REPORT NUMBER (MOD-NL)	2. RECIPIENT'S ACCESSION NUMBER	3. PERFORMING ORGANIZATION REPORT NUMBER
TD93-2783		FEL-93-B160
4. PROJECT/TASK/WORK UNIT NO.	5. CONTRACT NUMBER	6. REPORT DATE
9250.2	-	OCTOBER 1993
7. NUMBER OF PAGES	8. NUMBER OF REFERENCES	9. TYPE OF REPORT AND DATES COVERED
72 (EXCL. RDP & DISTRIBUTION LIST)	151	

10. TITLE AND SUBTITLE
HIGH PERFORMANCE COMPUTING FOR MEDICAL IMAGE INTERPRETATION

11. AUTHOR(S)
A.C.M. DUMAY

12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
TNO PHYSICS AND ELECTRONICS LABORATORY, P.O. BOX 96864, 2509 JG THE HAGUE
OUDE WAALSDORPERWEG 63, THE HAGUE, THE NETHERLANDS

13. SPONSORING/MONITORING AGENCY NAME(S)
TNO PHYSICS AND ELECTRONICS LABORATORY, P.O. BOX 96864, 2509 JG THE HAGUE
OUDE WAALSDORPERWEG 63, THE HAGUE, THE NETHERLANDS

14. SUPPLEMENTARY NOTES
THE CLASSIFICATION DESIGNATION ONGERUBRICEERD IS EQUIVALENT TO UNCLASSIFIED.

15. ABSTRACT (MAXIMUM 200 WORDS, 1044 POSITIONS)
MEDICAL IMAGE PROCESSING AIMS AT IMPROVEMENT OF THE IMAGE QUALITY IN ORDER TO SUPPORT THE MEDICAL DIAGNOSIS AND THERAPY. GLOBALLY, THERE CAN BE FOUR SUBJECTS DISTINGUISHED FOR IMAGE PROCESSING, INCLUDING : I) DATA FUSION; II) OBJECT/FEATURE EXTRACTION; III) ANALYSIS AND IV) VISUALISATION. DATA FUSION, OR REGISTRATION, CONCERNS THE COMBINATION OF IMAGES ACQUIRED WITH VARIOUS IMAGING MODALITIES INTO A SINGLE IMAGE. OBJECT/FEATURE EXTRACTION, OR SEGMENTATION, AIMS AT THE RECOGNITION AND EXTRACTION OF OBJECTS AND OBJECT FEATURES FROM IMAGE DATA. AND THE ANALYSIS INVOLVES THE INTERPRETATION OF THE OBJECT FEATURES FROM WHICH CONCLUSIONS CAN BE DRAWN. VISUALISATION IS OF UTMOST IMPORTANCE FOR EACH OF THE FOREMENTIONED SUBJECTS.
WITH THE INTRODUCTION OF COMPUTER TOMOGRAPHY (CT) AND MAGNETIC RESONANCE IMAGING (MRI) THREE-DIMENSIONAL (3D) IMAGES CAN BE ACQUIRED FROM PATIENTS. THE PROCESSING OF 3D IMAGES SUCH THAT THE TIME REQUIRED FOR THAT PURPOSE IS IN ACCEPTABLE LIMITS MAKES THE USE OF HIGH PERFORMANCE COMPUTING (HPC) TECHNIQUES DESIRABLE. CURRENTLY (COMMERCIALLY) AVAILABLE IMPLEMENTATIONS DO NOT SATISFY THE PERFORMANCE REQUIREMENTS FOR ROUTINE USE IN A CLINICAL SETTING AS A RESULT OF WHICH SUCH SYSTEMS WILL NOT BE USED AT ALL OR AT HIGH COSTS OF PERSONNEL. HIGH PERFORMANCE COMPUTING MEDICAL IMAGE INTERPRETATION INCLUDE DATA FUSION, OBJECT/FEATURE EXTRACTION,ANALYSIS AND VISUALISATION OF 3D MEDICAL IMAGES. MODULES FOR THESE PURPOSES MAY BE INTEGRATED IN EXISTING MEDICAL SYSTEMS TO SUPPORT INTERACTIVE VISUALISATION, QUANTITATIVE ANALYSIS, RADIOTHERAPY PLANNING AND NEUROSURGERY PLANNING. INTEGRATED INTO A HIGH PERFORMANCE COMPUTING MEDICAL IMAGE INTERPRETATION SYSTEM (HIPMIPS) ONE HAS THE TOOLS FOR DEVELOPING ANATOMICAL MODELS FOR SIMULATION AND TRAINING FOR, E.G., MINIMAL ACCESS SURGERY (MAS) AND TRIAGE.

16. DESCRIPTORS	IDENTIFIERS
PARALLEL PROCESSING	HIGH PERFORMANCE COMPUTING
IMAGE INTERPRETATION	MEDICAL IMAGE PROCESSING
	MEDICAL IMAGE INTERPRETATION
	3D MEDICAL VISUALISATION

17a. SECURITY CLASSIFICATION (OF REPORT)	17b. SECURITY CLASSIFICATION (OF PAGE)	17c. SECURITY CLASSIFICATION (OF ABSTRACT)
ONGERUBRICEERD	ONGERUBRICEERD	ONGERUBRICEERD

18. DISTRIBUTION/AVAILABILITY STATEMENT	17d. SECURITY CLASSIFICATION (OF TITLES)
UNLIMITED	ONGERUBRICEERD